Collaborative Vehicular Content Dissemination with Directional Antennas

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***Abstract*—We study the performance of collaborative vehicular content dissemination, where the content is distributed within the network by vehicle-to-vehicle opportunistic communications and the vehicle nodes are equipped with directional antennas. Through analysing a large real-world vehicle trace, we adopt an accurate mobility model of Lévy-walk to set up the realistic vehicular network simulation environment. Using a fluid approximation, we derive a theoretical model to depict the system performance of content dissemination time. The accuracy of the proposed analysis is confirmed by simulation results, which also show that the directional antenna performs better than the omni-directional antenna in our considered scenario, especially when the antenna beam is well scheduled with small beamwidth and high beam steering rate.**

***Index Terms*—Collaborative content dissemination, vehicular networks, Lévy-walk mobility, directional antennas.**

I. Introduction

RECENTLY, interests on large-scale vehicular ad hoc networks have grown significantly [1], as more and more vehicles are equipped with devices to provide vehicular communication capacities. Many applications of vehicular networks are also emerging, include automatic collision warning, remote vehicle diagnostics, emergency management and assistance for safely driving, vehicle tracking, automobile high speed Internet access, and multimedia content sharing. In USA, Federal Communications Commission has allocated 75 MHz of spectrum for dedicated short-range communications in vehicular networks [2], and IEEE is also working on the related standard specifications. Efficient content dissemination is a key issue for many vehicular network applications, such as content publishing for safety information and entertainment data [3]. These content dissemination applications might be supported within the existing wireless infrastructure, such as WiFi and 3G, but the coverage issue and economic consideration from both service providers and end users do not make such a solution efficient and viable. Another reason is that the wireless infrastructure may be congested, or even damaged in disaster. Consequently, content dissemination through vehicular ad hoc networks is highly desired. Since vehicular networks are highly mobile and sometimes sparse by nature, it is difficult to maintain a connected network to distribute the content [4]. Opportunistic contact between vehicles, by contrast, is capable of providing high-bandwidth communication capacity for content dissemination, which is known as opportunistic collaborative vehicular content dissemination [4].

In this letter, we analyze the system performance of opportunistic vehicular content dissemination, where the content can be transmitted only when two vehicles come into the communication range of each other. Therefore, the *vehicular mobility* model and the *communication range* are two of the most important factors that influence the system's performance. We have collected a large vehicle trace in Beijing, and validate a suitable analytical mobility model based on this *Beijing* trace in this study. With regarding the issue of transmission range, we consider the applicability of directional antennas that have more than one steerable directional beam to improve the system's achievable performance. Although there exist some recent works on content dissemination [3], [5], [6] and directional antennas [7]–[9], to the best of our knowledge, this is the first study on the performance of the collaborative content dissemination system under realistic vehicular scenarios using an accurate mobility model and directional antennas. Our contributions are as follows.

- We introduce the Lévy-walk model [10] for the vehicular mobility, and validate this model on the *Beijing* trace, which is the largest available vehicular mobility GPS trace. This model is used to set up a realistic vehicular mobility environment for the performance evaluation of collaborative vehicular content dissemination.
- We provide a theoretical model to analyze the content dissemination speed for collaborative vehicular content dissemination by fluid approximation, and use extensive simulation results obtained under realistic vehicular settings to validate the accuracy of our model.
- We evaluate the influence of the directional antenna on the performance of the vehicular content dissemination system by both analytical and simulation results. Our results confirm that the directional antenna performs better than the omni-directional antenna in our considered scenario.

II. System Description and Model

Fig. 1 illustrates the concept of collaborative vehicular content dissemination, where the goal is to disseminate the

Manuscript received June 30, 2011; revised November 4, 2011; accepted January 16, 2012. The associate editor coordinating the review of this paper and approving it for publication was X. Wang.

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This work is supported by National Nature Science Foundation of China (No. 61171065, No. 61021001) and Chinese National Major Scientific and Technological Specialized Project (No. 2010ZX03004-002-02), as well as the Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT) and TNLIST).

Digital Object Identifier 10.1109/TWC.2012.021512.111252

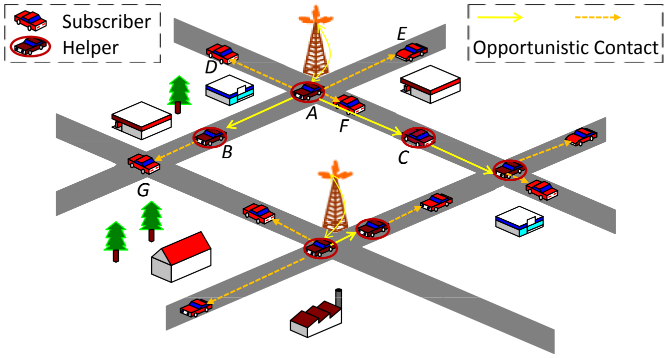

Fig. 1. System overview of the collaborative vehicular content dissemination. The infrastructure network first transmits the content to some helpers, which then disseminate the content to other encountered helpers (solid line) or encountered subscribers (dashed line) through opportunistic communication.

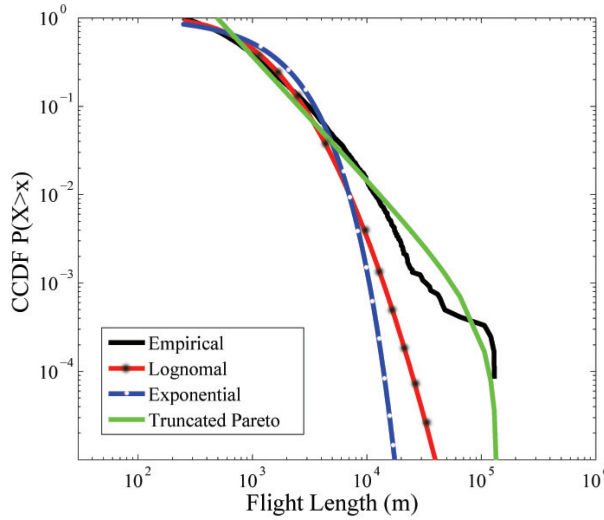

Fig. 2. Comparison of the empirical flight-length distribution extracted from *Beijing* trace with the fitted log-normal, exponential and upper-truncated Pareto distributions.

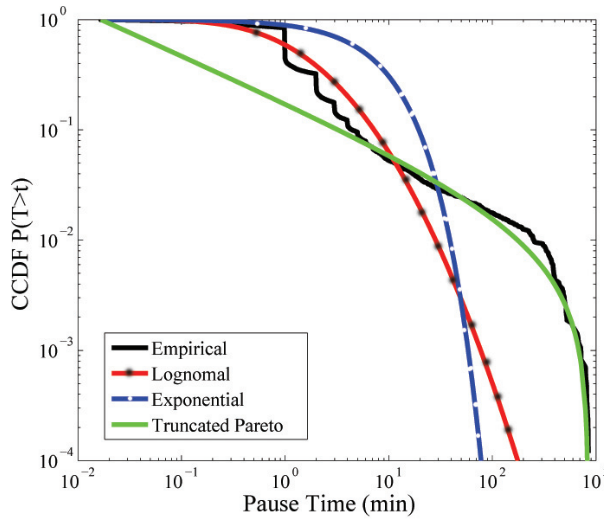

Fig. 3. Comparison of the empirical pause-time distribution extracted from *Beijing* trace with the fitted log-normal, exponential and upper-truncated Pareto distributions.

content to a group of subscribers through opportunistic communication. As not all the nodes are willing to participate in the content dissemination, there exist two types of vehicle nodes in the system, known as *helpers* and *subscribers*. Helpers are willing to buffer the content in their storages, and to further transmit the content to other helpers or subscribers. Subscribers are only interested in receiving the content and will not transmit the content to other nodes. Nodes are equipped with omni-directional or directional antennas to transmit or receive packets of content. At the beginning, a small number of helpers will obtain the content from the content source. Content dissemination may be split into two phases, namely, the disseminating phase, during which the content is transmitted among the helpers, and the receiving phase, when a subscriber finally receives the required content from a helper. Considering Fig. 1 again, in the disseminating phase, helper A transmits the content to helpers B and C by opportunistic contact. Helpers B and C, after received the data from A, will carry and forward the data to other helpers or subscribers later. In the receiving phase, subscribers D, E and F receive the packet from helper A, while subscriber G receives the packet from helper B.

A. Vehicular Mobility

Existing mobility models, such as random walk and random waypoint, cannot realistically represent the collaborative vehicular content dissemination system, where wireless devices are attached to vehicles and vehicular mobility patterns influence the system performance significantly. Let us consider the 2-dimensional vehicular mobility defined by a sequence of steps that a vehicle travels [11]. A step is denoted by a tetrad (l, ϕ, v, τ) during which a vehicle travels a flight followed by a pause, where $l > 0$ is the flight length, ϕ is the direction of the flight, v is the mobility velocity, and τ is the time duration of pause called pause time. Thus, step n is defined by $(l_n, \phi_n, v_n, \tau_n)$. Assume that the vehicle starts its first step at time $t = 0$. It chooses a direction ϕ_1 randomly from the uniform distribution in the range $[0,\ 360^\circ]$ and has a uniformly distributed velocity v_1, as well as chooses a flight length l_1 and a pause time τ_1 according to certain probability distributions. Consequently, in step 1, the vehicle moves the flight of the length l_1 at the direction ϕ_1 with the velocity v_1. It then stops for the pause time τ_1 during which the vehicle stays at the location where the current flight ends. After the pause, it chooses another step, and the process repeats. Clearly, the accuracy of a vehicular mobility model is determined by the accuracy of the distributions for flight length l and pause time τ.

We use the largest available real vehicular trace, the *Beijing* trace which we collected ourselves, to study the distributions of flight length and pause time by curve fitting techniques, which is widely used in the mobility modelling practice [11]–[13]. This trace contains the mobility track logs obtained from 27000 participating taxis carrying GPS receivers during the whole May month in 2010 [12]. To obtain this trace, we utilized the GPS devices to collect the taxi locations and timestamps and GPRS modules to report the records every one minute for moving taxis. Based on the *Beijing* trace, we utilize the angular model of [11] to extract the data of flight length and pause time, and subsequently to study the distributions of flight length and pause time, preliminary results of which are reported in our previous work [12]. Fig. 2 shows the empirical complementary cumulative distribution function (CCDF) of flight length, where we also applied the maximum likelihood estimation to fit three known distributions, the exponential, log-normal and truncated Pareto [14] distributions, to the data. We observe that the truncated Pareto has the best fit to the empirical CCDF among the three distributions. Similarly, Fig. 3 compares the empirical CCDF of the pause time extracted from the trace with the three fitted known distributions, where it can again be seen that the truncated Pareto distribution provides the best fit to the empirical pause-time distribution. More specifically, the MSE between the empirical distribution and the truncated Pareto distributed flight length is 17.2%, while the MSE for the truncated Pareto distributed pause time is 15.5%. In comparison, for example, for the exponential distribution, the MSE values are 34.9% and 318.3% for the flight length and pause time, respectively. This experiment suggests that both the pause time and flight length follow the truncated Pareto distribution. Therefore, we will use the Lévy walk [10] to model the *vehicle* mobility. Note that the existing work [11] has also validated that the Lévy walk can accurate model the *human* mobility by demonstrating that the truncated Pareto distribution can also fit the flight length and pause time of human mobility very well.

In summary, in our vehicular mobility model, the direction and velocity follow the uniform distributions, while the Lévy-walk model selects the flight length and pause time randomly with the truncation factors ξ^f_{min} and ξ^f_{max} for l and ξ^p_{min} and ξ^p_{max} for τ, respectively, according to the Lévy distribution with the exponent parameter ε, whose characteristic function is defined by

$$f(x) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{-\mathrm{j}\,x\,z - |c\,z|^{\varepsilon}}\,d\,z, \tag{1}$$

where $\mathrm{j} = \sqrt{-1}$ and c is a scaling coefficient. Specifically, the initial location of each vehicle is randomly chosen from a uniform distribution in the defined area. At step n, the tetrad $(l_n, \phi_n, v_n, \tau_n)$ is generated randomly according to the corresponding distributions. If the drawn duplet (l_n, τ_n) does not pass the truncation checking, that is, $l_n < \xi^f_{min}$, or $\tau_n < \xi^p_{min}$, or $l_n > \xi^f_{max}$ or $\tau_n > \xi^p_{max}$, then it is discarded and another duplet is regenerated. This procedure is repeated until the mobility pattern of the whole network is obtained.

B. Antenna Orientation

The antenna dynamics of node i are denoted by a duplet $A_i = (\vartheta_i(t), \theta_i(t))$, where the antenna orientation $\vartheta_i(t)$ is related to the beam steering direction, while the antenna beamwidth $\theta_i(t)$ is related to the antenna patterns. Both the beam steering and antenna patterns can change according to the system requirements. However, there are practical limitations in directional antenna implementation, and hence we model the antenna under realistic settings [7]. The beamwidth θ_i is chosen from the set $\{15°, 30°, 45°, 60°, 90°, 180°\}$. Given a θ_i, there are $720/\theta_i + 1$ beam patterns, one for omni-directional beam and $720/\theta_i$ for directional beams, each with an approximately $(\theta_i)°$ half-power beamwidth. Each directional beam is overlapping with the next beam and rotated by $(\theta_i/2)°$ to the next, and all the $720/\theta_i$ beams cover the $360°$ circle. We use an extensively used approximate model [9] for the antenna gain. Given the beamwidth θ_i, the main lobe gain, denoted by g_m, is defined as

$$g_m(\theta_i) = \frac{4}{\tan^2(\theta_i/2)}, \tag{2}$$

where g_m is obtained as the maximum beamwidth with no energy leakage. As the antenna direction changing is often caused by the upper layer traffic or packet sending requests, whose rate is usually modelled by the Poisson process, we assume that the antenna orientation ϑ_i changes its direction following the Poisson process with rate r_ϑ. If $r_\vartheta = 0$, the antenna orientation never changes. We define three policies for the beam steering: random steering (RS), circle steering (CS) and polling steering (PS). In RS, nodes randomly choose new beams from the feasible set of antenna patterns when Poisson changing events occur. CS chooses the next beam which is not overlapped with the current beams clockwise, while PS selects the next beam which is overlapped with the current beams clockwise. Since helpers need to transmit the content to as many as possible subscribers, it is better for a helper to transmit the content in all directions by using an omni-directional antenna. By contrast, a subscriber needs to receive the content from one of the helpers. Therefore, it can use a directional antenna to point to one of the helpers, or it may still use an omni-directional antenna. In our study, we investigate whether a directional or an omni-directional antenna is more beneficial in this context.

C. Content Transmission

When the content transmission occurs is decided by the physical propagation model. For any node, we can use the triplet $S(t) = (\mathbf{x}(t), \vartheta(t), \theta(t))$ to represent its state at time t, where $\mathbf{x}(t)$ is the node's position which is determined by the mobility model, $\vartheta(t)$ and $\theta(t)$ are the antenna orientation and beamwidth, respectively. Suppose that, at time t, vehicle i has the state $S_i = (\mathbf{x}_i, \vartheta_i, \theta_i)$, that is, the vehicle is at the position $\mathbf{x}_i$ and its antenna is pointing in the direction ϑ_i with the beanwidth θ_i, while another vehicle j has the state $S_j = (\mathbf{x}_j, \vartheta_j, \theta_j)$. Imagine that i is a helper which has already obtained the content, while j is either a helper or subscriber without the content. The content transmission from i to j will happen only when node j can capture the signal sent by node i with a power above a certain threshold denoted by ψ. In vehicular opportunistic networks, nodes are usually sparse and, furthermore, no end-to-end path exits between nodes. From this viewpoint, the free space path model may be adequate for the physical communication channel [9]. Therefore, our propagation model uses the following equation [9] to compute the received power

$$P_r(S_i, S_j) = \frac{P_t \cdot \lambda^2 \cdot d^2_{ref} \cdot G_t(A_i, \mathbf{x}_i, \mathbf{x}_j) \cdot G_r(A_j, \mathbf{x}_i, \mathbf{x}_j)}{4\pi^2 \cdot |\mathbf{x}_i - \mathbf{x}_j|^4}, \tag{3}$$

where P_t and P_r are the transmit and receive powers, respectively, λ is the wavelength, G_t and G_r are the gains of the transmit and receive antennas, respectively, while d_{ref} is a reference distance given by $d_{def} = 2D/\lambda^2$ with D being the maximum antenna dimension. The gains $G_t(A_i, \mathbf{x}_i, \mathbf{x}_j)$ and $G_r(A_j, \mathbf{x}_i, \mathbf{x}_j)$ depend on the antenna patterns and the relative positions of two nodes. Recalling the definition of g_m in (2), the expression for G_t is given by

$$G_t(A_i, \mathbf{x}_i, \mathbf{x}_j) = \begin{cases} g_m, & \vartheta_i \cdot \Delta\mathbf{x}_{ij} \leq \cos(\theta_i/2), \\ 0, & \vartheta_j \cdot \Delta\mathbf{x}_{ij} > \cos(\theta_j/2), \end{cases} \quad (4)$$

where $\Delta\mathbf{x}_{ij} = \mathbf{x}_i - \mathbf{x}_j$. The expression for $G_r(A_j, \mathbf{x}_i, \mathbf{x}_j)$ is similar. If $P_r(S_i, S_j) \geq \psi$, node j can receive the content from node i.

III. Fluid Approximation-Based Dissemination Time

We note that when a helper with the content contacts with other nodes without the content, it will disseminate the content. The status of whether a node has the content in the opportunistic vehicular network can be viewed as a stochastic process that is controlled by opportunistic contact events. Consequently, the content dissemination is a complicated stochastic process consisting of a large number of component processes. We employ a fluid approximation model [15] to analyze this highly complex content dissemination system. It is well known that the fluid approximation is incapable of describing the dynamics of this stochastic system [15]. However, it allows us to replace this stochastic process by "joining" all the nodes to form a deterministic process, and the result obtained by this approximation is known to be close to that of the underlying stochastic process in the expectation sense.

The content dissemination process starts at time $t = 0$ when some helpers obtained the content from the source. A node with the content is called an *infected* node. Assume that the total number of vehicles in the system is N and, furthermore, there are H helpers and S subscribers. Then, the fraction of the helpers, denoted by φ_h, is $\varphi_h = H/N$, while the fraction of the subscribers, denoted by φ_s, is $\varphi_s = S/N$. Define $h(t) = N_h(t)/N$ as the proportion of the helpers that have received the content at time t, where $N_h(t)$ is the number of infected helpers at t. Similarly, let $s(t) = N_s(t)/N$ be the proportion of the subscribers that have received the content at time t, where $N_s(t)$ is the number of infected subscribers at t. The fluid approximation describes the dynamics of the system by the following ordinary differential equations:

$$\frac{d}{dt}h(t) = \zeta(\varphi_h - h(t))h(t), \quad (5)$$

$$\frac{d}{dt}s(t) = \eta(\varphi_s - s(t))h(t), \quad (6)$$

where ζ is the contact rate between helpers, while η is the contact rate between a helper and a subscriber. These contact rates depend upon node mobility speeds and antenna propagation characteristics, and are proportional to the new area covered per unit time [16]. Under the omni-directional antenna, the contact rate is proportional to $\pi R v$, where R is the communication range and v the node mobility velocity [16]. In the directional-antenna case, the contact rate also depends on the beamwidth and beam steering rate.

Based on the mean field theory [17], the equations (5) and (6) correspond to the random node mixing assumption and are asymptotically valid when the number of nodes in the system is large. Combining (5) and (6) yields $\frac{dh(t)}{ds(t)} = \frac{\zeta}{\eta}\frac{\varphi_h - h(t)}{\varphi_s - s(t)}$, which leads to

$$s(t) = \varphi_s - \frac{\varphi_s - s_0}{(\varphi_h - h_0)^{\eta/\zeta}} (\varphi_h - h(t))^{\eta/\zeta}, \quad (7)$$

where $s_0 = s(0)$ and $h_0 = h(0)$. We now solve (5) to obtain $h(t)$ explicitly. Note that

$$\frac{1}{(\varphi_h - h(t))h(t)} = \frac{1}{\varphi_h}\left(\frac{1}{\varphi_h - h(t)} + \frac{1}{h(t)}\right).$$

Therefore, from (5) we have $\frac{dh(t)}{\varphi_h - h(t)} + \frac{dh(t)}{h(t)} = \varphi_h \zeta dt$, which explicitly yields

$$h(t) = \frac{\varphi_h h_0}{h_0 + (\varphi_h - h_0)\, e^{-\varphi_h \zeta t}}. \quad (8)$$

By substituting (8) into (7), we explicitly obtain

$$s(t) = \varphi_s - \varrho\left(\varphi_h - \frac{\varphi_h h_0}{h_0 + (\varphi_h - h_0)\, e^{-\varphi_h \zeta t}}\right)^{\eta/\zeta}, \quad (9)$$

where $\varrho = (\varphi_s - s_0)(\varphi_h - h_0)^{-\eta/\zeta}$. Define T_ω as the time at which the proportion $(1-\omega)$ of the subscribers have received the content. In other words, only the proportion ε of the subscribers have not yet received the content at time T_ω. We refer to T_ω as the dissemination time, which depicts the content dissemination speed, and we use it as a metric of the system performance. From the definition of the dissemination time, we have $\varphi_s(1-\omega) = s(T_\omega)$. According to (9), we obtain $e^{-\varphi_h \zeta T_\omega} = \frac{\beta h_0}{(\varphi_h - \beta)(\varphi_h - h_0)}$, where $\beta = \left(\frac{\varphi_s \omega}{\varphi_s - s_0}\right)^{\zeta/\eta}$. Therefore,

$$T_\omega = \frac{1}{\varphi_h \zeta} \ln\left(\frac{(\varphi_h - \beta)(\varphi_h - h_0)}{\beta h_0}\right). \quad (10)$$

IV. Numerical Results

The simulated system covered an area of $2000 \times 2000\ \mathrm{m}^2$ with time steps $n = 60 \times 60 \times 2$. We randomly used 70% of the network nodes as subscribers, and the remaining 30% as helpers. The content source randomly selected 10% of the helpers and disseminated the data to them at $t = 0$. The vehicular mobility of Subsection II-A was adopted, in which ϕ_n obeyed the uniform distribution in $[0,\ 360°)$, and v_n followed the uniform distribution in $[8,\ 15]$ m/s, while l_n was generated according to (1) with $\varepsilon = 1.5$, $c = 2.5$, $\xi^f_{min} = 5$ m and $\xi^f_{max} = 1000$ m, and t_n also obeyed the Lévy walk (1) with $\varepsilon = 1.5$, $c = 2.5$, $\xi^p_{min} = 30$ s and $\xi^p_{max} = 600$ s. All the antennas, whether omni-directional or directional, had the same transmit power. We set the antenna gain to let the communication range of two omni-directional antennas being 60 m, and calculated the gain and communication range of directional antennas according to (3) and (4). In order to obtain credible and reliable results, we simulated the system with the specific settings of node mobility and antenna 100 times to obtain the simulated content dissemination time T^*_ω, given $\omega = 0.1$. Then, we plotted the simulation results by averaging over these 100 different runs as well as plotted their corresponding confidence intervals in all the figures.

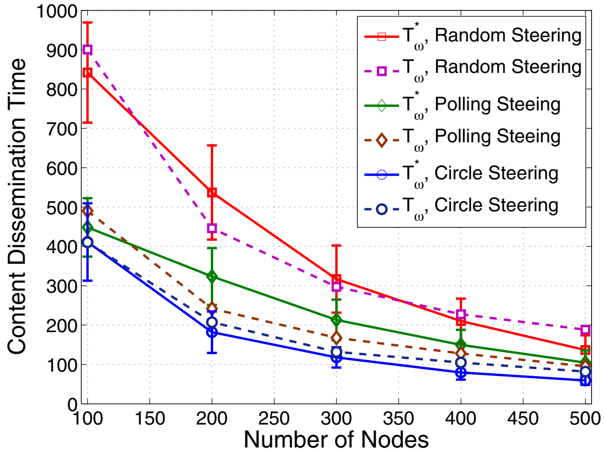

Fig. 4. Content dissemination time as function of the number of nodes for three beem steering policies with beamwidth $\theta = 45^{\circ}$ and beam steering rate $r_{\vartheta} = 20$, where dashed curves are the fluid model based results given by (10), while solid curves are the simulation results with the vertical bars indicating the standard deviation.

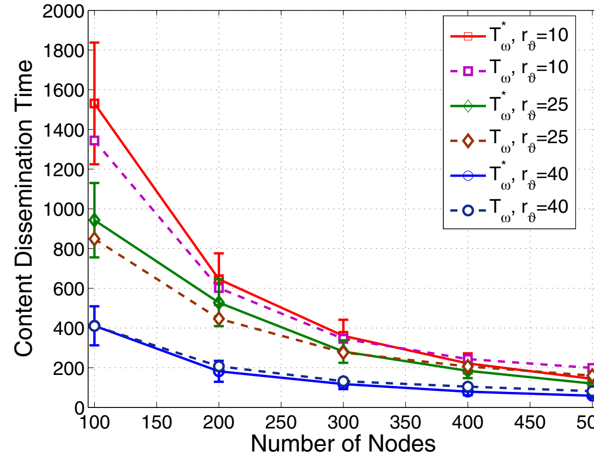

Fig. 5. Content dissemination time as function of the number of nodes for different beam steering rates r_{ϑ} with beamwidth $\theta = 45^{\circ}$ and random steering, where dashed curves are the fluid model based results given by (10), while solid curves are the simulation results with the vertical bars indicating

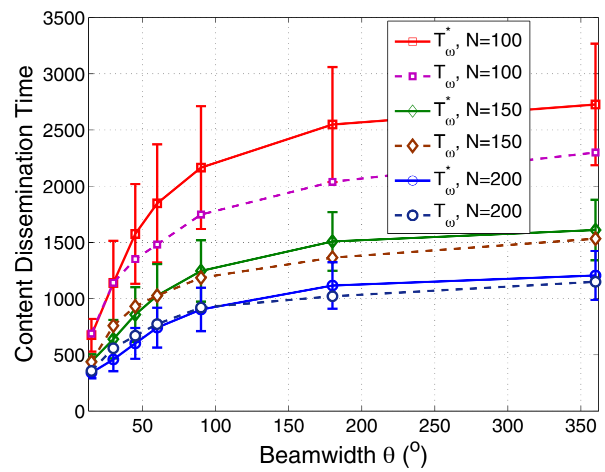

Fig. 6. Content dissemination time as function of the beamwidth varying from 15° to 360° for different numbers of system nodes with $r_{\vartheta} = 10$ and random steering, where dashed curves are the fluid model based results given by (10), while solid curves are the simulation results with the vertical bars indicating the standard deviation.

By extracting the contact rates ζ and η, we also calculated the theoretical content dissemination time T_{ω} using (10). This enabled us to investigate the accuracy of our proposed model for content dissemination time by comparing T_{ω}^{*} and T_{ω}. Furthermore, we analyzed how the directional antennas with different beam steering policies, beam steering rates and beamwidths influence the system performance.

The content dissemination times of three beam steering policies as function of the number of nodes are shown in Fig. 4, where the simulation results are averaged over 100 runs. As the number of nodes N increases, the content dissemination time T_{ω}^{*} decreases. The reason is obvious. A larger N means a higher node density, since the system area is constant, which in turn leads to more opportunistic contacts to disseminate the content. The RS policy needs the longest time to disseminate the content, while the CS policy achieves the shortest data dissemination time, under the same settings of nodes and antenna beams. Specifically, the CS reduces the content dissemination time by 51% and 32%, compared with the RS, for $N = 100$ and 500, respectively. This result shows that if we schedule the beam steering, rather than random steering, significant performance enhancement can be achieved. The performance enhancement of the CS policy over the PS policy is about 23% to 2%. Thus, in the beam scheduling, better system performance can be achieved by changing the beam to let the antenna swap more area and avoid overlapping the already covered area. It can be seen that, in the directional antenna based opportunistic content dissemination system, designing an appropriate beam scheduling algorithm is important. From Fig. 4, we can see that the theoretical results of T_{ω} are very close to the simulation results of T_{ω}^{*}, which validates the accuracy of our content dissemination model (10).

Next, we studied the influence of beam steering rate r_{ϑ} under the RS policy with a fixed beamwidth $\theta = 45^{\circ}$, and the results obtained are shown in Fig. 5. Again, the simulation results T_{ω}^{*} agree with the theoretical ones T_{ω}, and similar observations to those for Fig. 4 can be drawn regarding the number of nodes. As the beam steering rate increases, the content dissemination time reduces significantly. For example, the dissemination time for $r_{\vartheta} = 40$ is only 30% and 50% of those with $r_{\vartheta} = 10$ and $r_{\vartheta} = 25$, respectively. However, it should be pointed out that the beam steering rate is limited by real-system antenna implementation, and the performance enhancement is obtained at the cost of energy leakage.

The results of content dissemination time as function of beamwidth are shown in Fig. 6. When the beamwidth $\theta = 360^{o}$, the antenna is omni-directional. From Fig. 6, it can be seen that the direction antenna offers superior system performance over the omni-directional one. Moreover, as the beamwidth is reduced, the content dissemination time is also reduced. In other words, the smaller the beamwidth, the larger the achievable performance enhancement. The reason is that the transmission range is enlarged by reducing the beamwidth, and the beam is steered to enable the nodes cover more new area which in turn creates more communication contacts. Thus, the content is distributed more efficiently.

V. CONCLUSIONS

We have analyzed the performance of collaborative vehicular content dissemination with the aid of directional antennas. Our contributions include validating the Lévy-walk model for vehicular mobility and deriving a fluid approximation for studying the collaborative vehicular content dissemination system. We have shown that, with the aid of directional antennas, the content propagation speed is accelerated, compared with omni-directional antennas. Simulation results have confirmed the accuracy of our proposed model. Our ongoing work is further investigating beam scheduling algorithms as well as the beamwidth and steering rate control problem in more complicated and realistic scenarios to fundamentally reveal the benefit or loss of directional antennas for general mobile wireless networking.

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